

Complex Fundamental Diagram of Traffic Flow in the Deep Lefortovo Tunnel (Moscow)

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Summary. The fundamental diagram for tunnel traffic is constructed based on the empirical data collected during the last two years in the deep long branch of the Lefortovo tunnel located on the 3rd circular highway of Moscow. This tunnel of length 3 km is equipped with a dense system of stationary radiodetectors distributed uniformly along it chequerwise at spacing of 60 m. The data were averaged over 30 s. Each detector measures three characteristics of the vehicle ensemble; the flow rate, the car velocity, and the occupancy for three lanes individually. The conducted analysis reveals an original complex structure of the fundamental diagram.

Traffic Flow in Long Tunnels

The properties of traffic flow in long highway tunnels has been under individual consideration since the middle of the last century (see, e.g., Refs [1, 2]). Interest to this problem is caused by several reasons. The first and, may be, main one is safety. Jams in long tunnels are rather dangerous and detecting the critical states of vehicle flow leading to the jam formation is of the prime importance for the tunnel operation. Second, the tunnel traffic in its own right is an attractive object for studying the basic properties of vehicle ensembles on highways. On one hand, it is due to the individual car motion being more controllable inside tunnels with respect to velocity limits and lane changing. On the other hand, long tunnels typically are equipped with a dense system of detectors, which provides a unique opportunity to receive a detailed information about the spacial-temporal structures of traffic flow.

The present work continues the investigation of tunnel traffic properties reported previously [3]. The analysis is based on empirical data collected during the last time in the Lefortovo tunnel located on the 3rd circular highway of Moscow (Fig. 1). It comprises two branches and the upper one is a deep linear three lane tunnel of length about 3 km. Exactly in this branch the analyzed data were collected. The tunnel is equipped with a dense system of stationary radiodetectors (Remote Traffic Microwave Sensor, X model) distributed uniformly along it chequerwise at spacing of 60 m. Because of the technical features of the detectors traffic flow on the left and right lanes is measured at spacing of 120 m whereas on the middle lane the spacial resolution is 60 m. The data were averaged over 30 s.

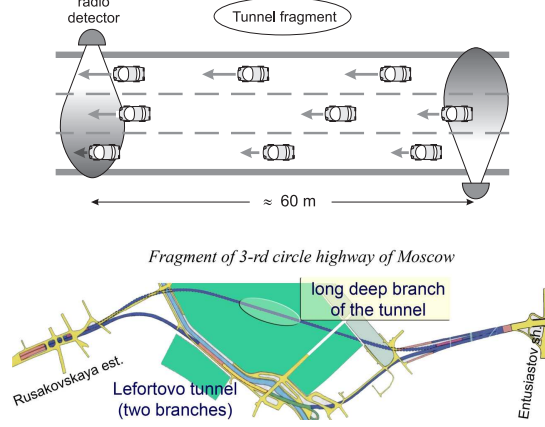


Fig. 1. Structure of the Lefortovo tunnel and the system of car motion detectors.

Each detector measures three characteristics of vehicle ensemble; the flow rate q , the car velocity v , and the occupancy k for three lanes individually. The occupancy is analog to the vehicle density and is defined as the total relative time during which vehicles were visible in the view region of a given detector within the averaging interval. It is measured in percent. The detectors themselves and their records were analyzed initially to justify the reliability of the collected data.

Fundamental Diagram

The fundamental diagram under consideration was constructed as follows. The phase space $\{k, v, q\}$ was divided into cells of size about $1\% \times 1 \text{ km/h} \times 0.01 \text{ car/s}$. Each 30 seconds a detector contributes unity to one of the cells. Taking into account a certain rather long time interval of traffic flow observation, all the detectors, and then dividing the result by the total number of records we obtain the three-dimensional distribution $P(k, v, q)$ of fixed traffic flow states over this phase space. In order to elucidate the obtained result we present the projection of $P(k, v, q)$ on three phase planes $\{kq\}$, $\{kv\}$, and $\{vq\}$. Besides, in projecting onto the given phase planes some layers can be singled out, for example, the expression

$$P_{DV}(k, q) \propto \int_{v \in DV} dv P(k, v, q)$$

specifies the projection of the layer $DV = (v_{\min}, v_{\max})$ onto the plane $\{kq\}$ within a constant cofactor normalizing it to unity. Such distributions will be also referred to as slices of the fundamental diagram.

Figure 2 presents the projection of the whole fundamental diagram onto the plane $\{k, q\}$ (the upper left frame) as well as its slices parallel to this plane. In the frame of the whole projection two branches are singled out by the relation $v \leq 21 \text{ km/h} \times k/k_{c2}$, where the critical occupancy $k_{c2} = 31\%$ according the results to be demonstrated further. The two branches with a small degree of overlap are

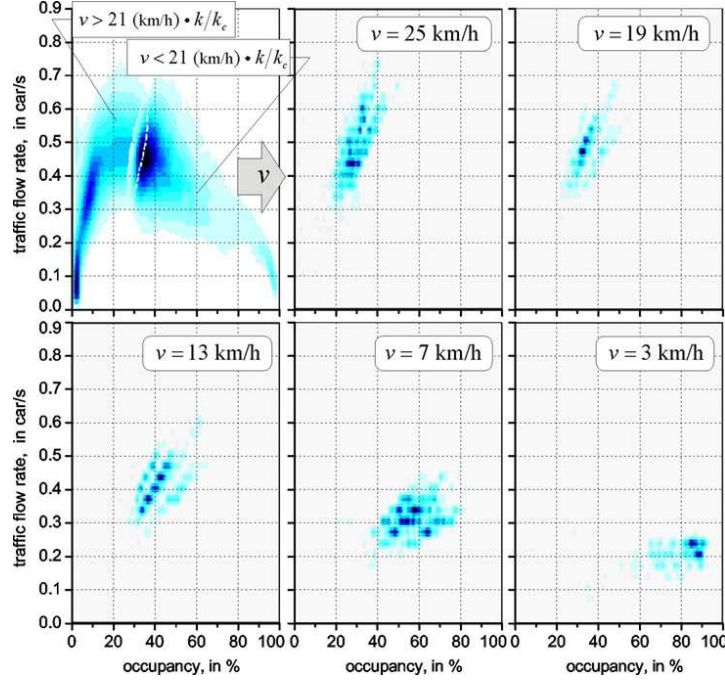


Fig. 2. Projection of the fundamental diagram onto the plane $\{k, q\}$ as well as its slices parallel to this plane.

separated actually by the transition from light to heavy synchronized traffic (see below). The given slices of fixed velocity demonstrate the fact that, at least, three different states of heavy congested traffic were observed. It reflects in the existence of three branches visible well for $v = 19, 13, 7$ km/h. Their additional analysis demonstrated us that these branches are characterized individually by different mean lengths of vehicles. In particular, the higher is a branch in Fig. 2, the shorter, on the average, vehicles forming it. The distribution of the traffic flow states becomes rather uniform for very low velocities matching the jam formation. On the whole fundamental diagram the jammed traffic is described by the region looking like a certain “beak”.

Figure 3 depicts a similar projection of the fundamental diagram onto the plane $\{k, v\}$. For low values of the traffic flow rate two states of traffic flow are clearly visible, the free flow and jam. The slice of $0.3 < Q < 0.4$ (car/s) shows actually the light and heavy phases of synchronized traffic flow, with the latter phase splitting into several branches. The final slice corresponding to large values of the traffic flow rate exhibits the phase transition between the two light and heavy states of traffic flow at the critical value of occupancy $k_{c2} = 31\%$, where the velocity drop about 15 km/h is clearly visible. It should be pointed out that the traffic flow states are distributed with the comparable intensity on both the sides of the phase transition at $k = k_{c2}$, which enables us to assume that this phase transition proceeds in the both

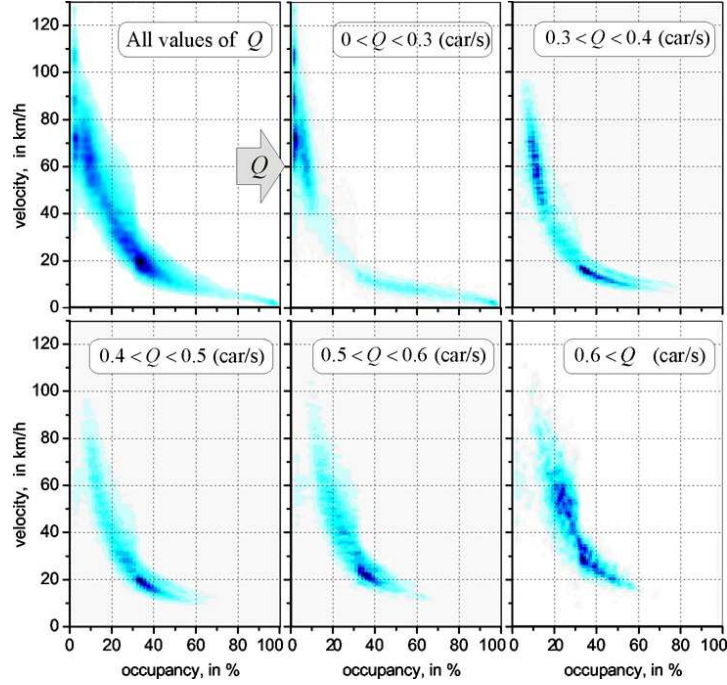


Fig. 3. Projection of the fundamental diagram onto the plane $\{k, v\}$ as well as its slices parallel to this plane that are made up by projecting the noted layers.

directions. The whole projection of the fundamental diagram on the plane $\{k, v\}$ also shows this phase transition as well as the existence of two accumulation points of traffic flow states in the region of light synchronized traffic and in the vicinity of phase transition between the two states of synchronized traffic. The latter feature poses a question about the possibility of phenomena like “stop-and-go waves” but based on transitions between different states of the synchronized traffic.

Figure 4 exhibits the projection of the fundamental diagram onto the plane $\{q, v\}$ and evolution of its slices for fixed values of the occupancy. In this figure the four different phase states of the analyzed tunnel traffic are visible. The free flow where the overtaking manoeuvres are most feasible corresponds to the three branches that can be related to trucks, passenger cars, and high-speed cars. As the traffic flow rate grows with the occupancy k the three branches terminate and are followed by a structureless two-dimensional domain via a certain phase transition. Then this phase state in turn is followed by a structural domain which itself converts again into the structureless beaked region corresponding to jam.

Obtained Results and Conclusion

The paper is devoted to constructing the fundamental diagram for tunnel traffic based on the empirical data collected in the linear higher branch of the Lefortovo

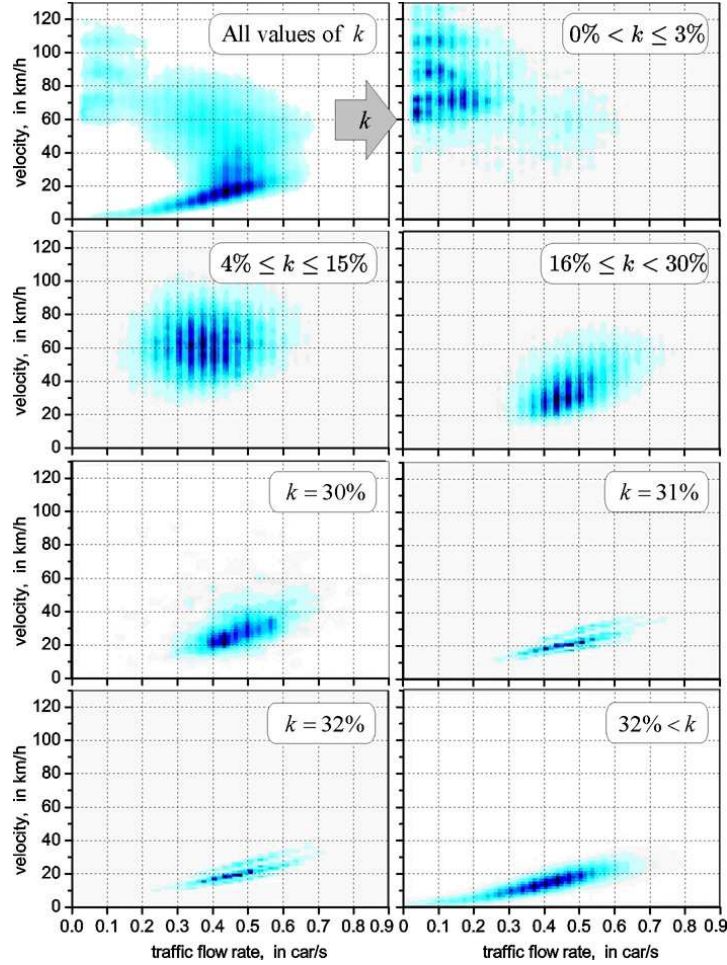


Fig. 4. Projection of the fundamental diagram onto the $\{q, v\}$ -plane as well as its several slices parallel to this plane.

tunnel located on the 3rd circular highway of Moscow in 2004-2005. It is the three lane tunnel of length 3 km equipped with radiodetectors measuring the traffic flow rate (q , in car/s), the vehicle velocity (v , in km/h), and the road occupancy (k , in %) averaged over 30 s. The detectors are distributed chequerwise at spacing 60 m along the tunnel. Because of the detector technical characteristics the traffic flow parameters are fixed at 60 m spacing on the middle lane and 120 m spacing on the left and right ones.

The fundamental diagram is treated as the traffic flow state distribution and has been constructed using the relative number of records per $1\% \times 1 \text{ km/h} \times 0.01 \text{ car/s}$ cells in the phase space $\{k, v, q\}$. Analyzing the three projections of this 3D field and

its different slices we have demonstrated the fundamental diagram to be complex in structure. Four possible traffic flow states are found, the free flow, light synchronized traffic, heavy synchronized traffic, and jam. The free flow state as well as the heavy synchronized traffic has a substructure, whereas the light synchronized traffic and jam are structureless.

The free flow comprises three branches related to trucks, passenger cars, and high-speed cars. These branches exist while the occupancy is less than a certain critical value, $k < k_{c1} \approx 3\%$ and are clearly visible in the projection onto the phase plane $\{q, v\}$. As the occupancy grows the light synchronized traffic appears which is characterized by the structureless region of widely scattered states. When the occupancy exceeds the next critical value $k_{c2} \approx 31\%$ the heavy synchronized traffic changes the previous phase state. This transition is accompanied by some jump in the mean velocity. In the projections onto the phase planes $\{k, q\}$, $\{k, v\}$, and $\{q, v\}$ it looks like widely scattered states uniformly distributed inside a certain region. However the corresponding slices of the fundamental diagram demonstrate a substructure of the given phase state. It again comprises, at least, three different branches. The conducted analysis demonstrated that the given branches are characterized, on the averaged, by different lengths of vehicles. The jam phase, as should be expected, can be ascribed with a certain relationship between the traffic flow rate q , the mean velocity v , and the occupancy k , in particular, it is possible to write down a certain function $v = v(k)$.

In addition we should note the following. In spite of the complex structure of the fundamental diagram and the existence of four different phase states the distribution of the detected states is, roughly speaking, bimodal. One its maximum is located at the beginning of the region matching the light synchronized traffic. The other maximum drops on the region corresponding to the transition between the two phases of the synchronized traffic.

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